Research on effect of discharge gas quantity per vehicle for ventilation system design for road tunnel

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Abstract

Recently, in Japan, the discharge amount of smoke and CO per vehicle which is used for the design of ventilation system for tunnel has been decreasing because of the regulation of vehicle discharge gas and improvement of vehicle performance.

This paper shows the results of the discharge gas quantity per vehicle which is used for ventilation system design for tunnel through the measurement results by in-site investigation of the concentration of discharge gas in tunnels and the estimate of discharge gas quantity under current regulation of vehicle discharge gas.

1. Introduction

Ventilation systems for road tunnels are designed based on carbon monoxide (CO) as a compound that has adverse physiological effects on tunnel users and smoke as a substance that affects the visible distance in the tunnel.

New emission regulation targets have been set in recent years, such as the short-term target for 1993 to 1994, the long-term target for 1997 to 1999, the new short-team target for 2002 to 2004 and the new long-term target for 2005 to 2007. The emission regulations and improved vehicle performance have reduced the emissions of CO and smoke per vehicle, based on which ventilation systems for road tunnels are to be designed.

This paper describes an investigation of gas emissions per vehicle for designing ventilation systems, which involved measuring exhaust gas concentrations in road tunnels in service to understand changes in emissions per vehicle and to predict emissions under the new exhaust restrictions.

2. Measuring gas emissions in tunnel

2.1 Measuring methods

Actual exhaust emissions were measured in two-lane road tunnels continuously for 48 to 72 hours by measuring exhaust gas concentrations, etc. An overview of the tunnels is shown in Table 1. Five tunnels were assumed to be single tubes as shown in Figure 1, and the concentrations of various kinds of exhaust gas were measured at the entrance and exit of the tunnels. The numbers of heavy and light vehicles (heavy vehicle: trucks and buses, light vehicle: passenger cars) that passed through the tunnels were counted separately. Items measured were smoke concentration, which affects the visible distance, carbon monoxide (CO) concentration, which has physiological impacts on people and is a compound that must be considered when designing ventilation systems, concentration of particulates (2.5 μm or smaller particles), which are related to smoke concentration, concentration of coarse particles (10 to 2.5 μm), wind velocity in the tunnel, and traffic volume (separately for heavy and light vehicles). In 2000, the dust concentration was also measured in Tunnel A, and the contributions of each source of particulates and coarse particles were investigated.

Table 1. Overview of tunnels monitored and year of monitoring

Tunnel	Length (m)	Maximum gradient (%)	Ventilation method	Traffic	2000	2001	2002	2003	2004	2007
A	2,027	0.3	Longitudinal ventilation of the JF type with shaft	Two ways	○	○		○		○
B	734	1.6	JF + forced longitudinal ventilation	One way	○					
C	881	1.3	Natural ventilation	One way			○			
D	1,833	1.3	Longitudinal ventilation of the JF type	Two ways				○		
E	1,224	2.3	Longitudinal ventilation of the JF type	Two ways					○	

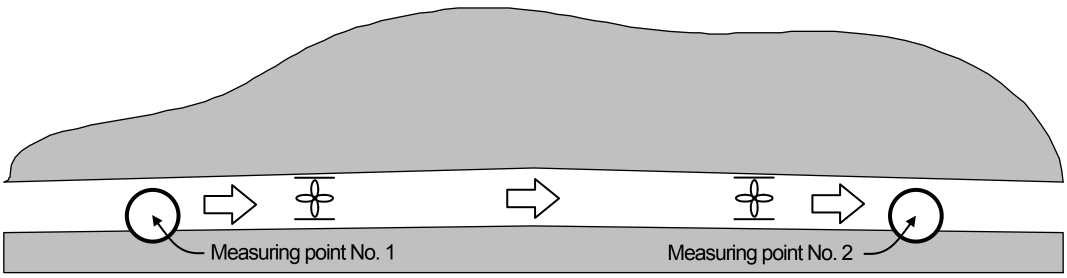

Figure 1. Overview of monitoring

The amount of harmful chemicals emitted per vehicle was calculated from the concentrations of smoke and CO, wind velocity in the tunnel and traffic volume. The analysis was conducted using the mean value for 10 minutes (mean of instantaneous values measured every 1 second) and specifications such as the numbers of heavy and light vehicles.

Smoke emission was determined using Equation (1) for calculating the smoke concentrations (k_i) from transmittance values measured using visibility sensor(VI) at the two measuring points (Measuring points No.1 and 2) in Figure 1. and Equation (2) using the difference of the resultant smoke concentrations at the measuring points (k_2-k_1). Emissions of CO, particulates and coarse particles per vehicle were also calculated using Equation (2), which is based on differences in concentration between the two points.

$$ki = -\frac{1}{L}\ln\tau \quad \text{... (1)}$$

$$K = \frac{(k2 - k1) * Q}{L * N} \quad \text{... (2)}$$

where, τ : transmittance, K : smoke emission (m^2/km/vehicle), k_1 and k_2 : smoke concentration in the tunnel (1/m), Q : the flow on the road (m^3/10 min), L : the distance between the points (km), N : traffic volume (vehicles/10 min).

2.2 Results of monitoring

(1) Exhaust gas concentration in tunnels and pollutants to be ventilated

The means for 10 minutes of smoke transmittance and CO concentration measured in Tunnel A are shown in Figure 2. The figure shows that the value of both smoke and CO were constant at the upwind point (No. 1), whereas those at the downwind point (No. 2) fluctuated with the number of vehicles. A similar trend has

been observed in other tunnels and in other years of monitoring, and both smoke and CO values have been generally lower than the design concentrations (smoke transmittance of 40% and CO concentration of 100 ppm) prescribed in the Technical Standards [1].

In a tunnel with an unusual condition of very large traffic volume, the transmittance temporarily fell below the design value of 40% at certain wind directions and speeds. Under such circumstances, the CO concentration increased temporarily to about 40 ppm. At a transmittance of 40%, the CO concentration was about 20 ppm and was sufficiently lower than the design concentration of 100 ppm, showing that CO concentrations would be sufficiently low provided the smoke concentration does not exceed the design value.

Therefore, considering smoke and CO as pollutants to be ventilated was judged to be appropriate for designing ventilation systems of road tunnels for the time being.

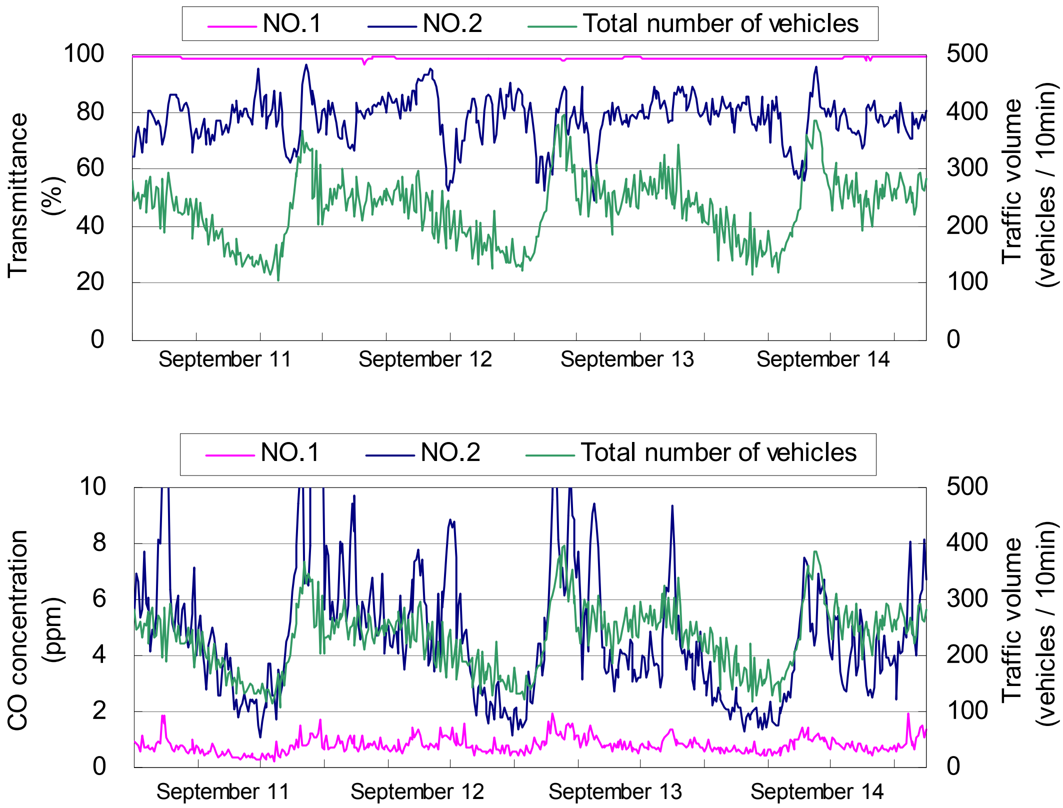

Figure 2. Smoke and CO concentration measurements

(2) Emission of harmful chemicals per vehicle to be used for designing ventilation

1) Results of emission calculations

The relationships between smoke and CO concentrations, which were calculated as described above, and the percentage of heavy vehicles are shown in Figure 3. From the linear regression equations determined using the relationships, the value at 100% heavy vehicles will mean the emission of a heavy vehicle, and the value at 0% heavy vehicles will mean is the emission of a light vehicle.

2) Changes in emissions over the years

Changes in emissions of smoke and CO per vehicle, which are pollutants to be ventilated, over the years were calculated from monitored values and are shown in Figures 4 and 5. The figures show the emissions determined by a similar survey [2] conducted in the early 1990s and the technical standards used for designing ventilation systems. As shown in Figure 4, the smoke emission from a light vehicle has little changed from past values, although some values exceeded the technical standard. On the other hand, the smoke emission from a

heavy vehicle was much smaller than the technical standard and has constantly decreased every year although the values fluctuated slightly. As shown in Figure 5, CO emissions have tended to decrease similarly to smoke emissions and were smaller than the technical standards for both light and heavy vehicles.

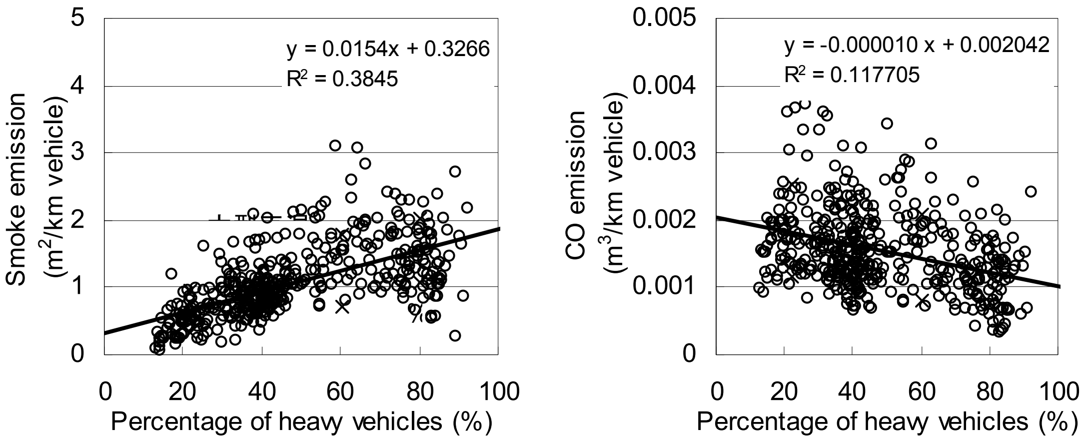

Figure 3. Relationships between emissions and percentage of heavy vehicles

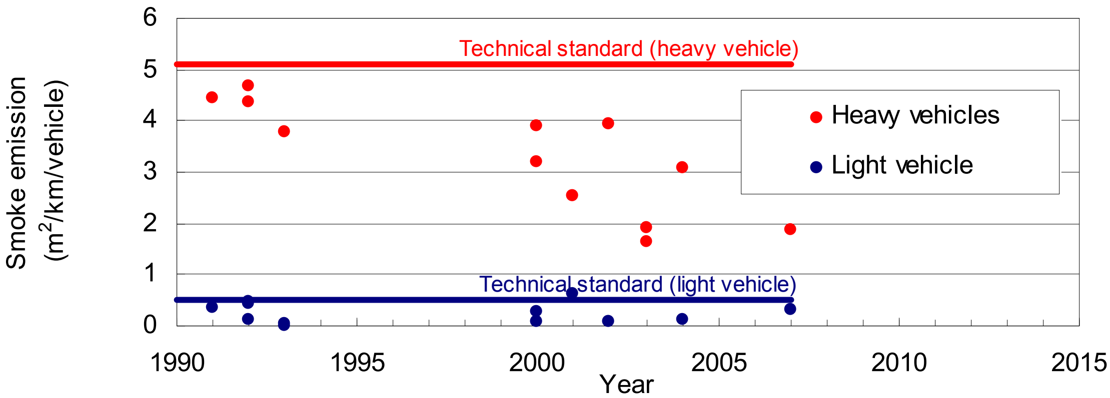

Figure 4. Changes in smoke emission over the years

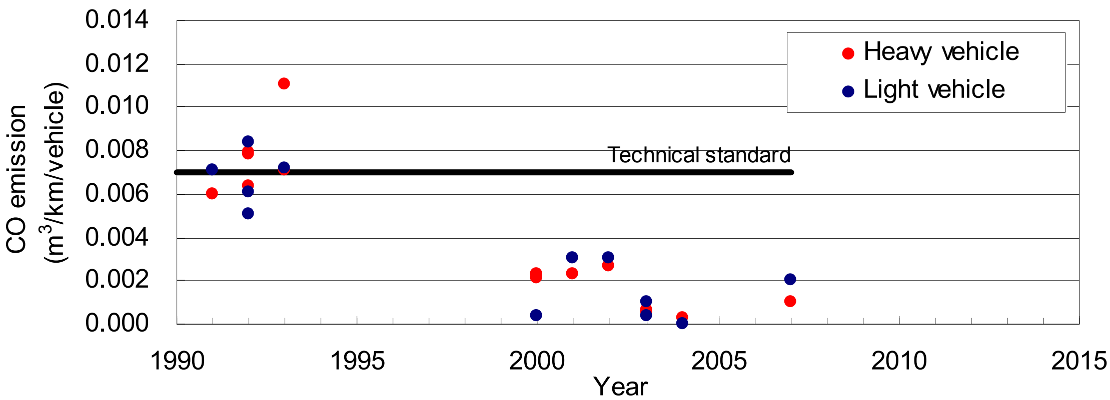

Figure 5. Changes in CO emission over the years

The emissions of pollutants per vehicle, which are used for designing ventilation systems, have decreased every year due to the introduction of strict emission regulations, etc. The emissions of smoke and CO were also found to be smaller than the technical standards.

3. Predicting emissions under new emission regulations

3.1 Concept of predicting emissions in the future

The smoke emissions in the future, assuming that new emission regulations are introduced, were predicted by multiplying the smoke emission in the standard year and the predicted reduction in particle emissions from vehicles, considering the compositions of vehicle models and types that meet the emission regulations in each year.

3.2 Pollutants to be reduced

Smoke, which is considered when designing tunnel ventilation, consists of particles discharged from vehicles (exhaust particles) and swirled dust particles, such as those brought into the tunnel from the outside by vehicles and those produced by abrasion between tires and road surface. In this study, smoke emissions in the future were predicted by assuming that exhausted particles from vehicle, which account for a large percentage, will decrease as shown in Figure 6.

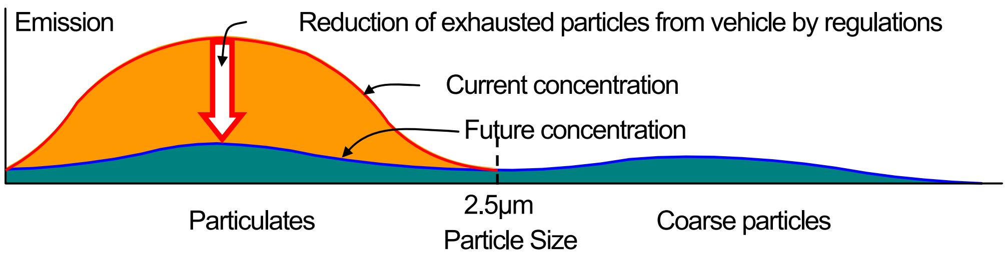

Figure 6. Conceptual diagram of reductions in smoke constituents

3.3 Procedure for estimating future smoke emissions

The procedure for estimating smoke emissions in the future is shown in Figure 7. Items I to IV in the diagram were set as described below.

(1) I. Amounts of particulates and coarse particles emitted from heavy and light vehicles

The amounts of particulates and coarse particles emitted from heavy and light vehicles, which were used as standards, were determined by the latest survey in 2007 and are shown in Table 2.

(2) II. Contributions of pollutant sources determined by dust component analysis

The estimated contribution ratios (means of 3 days) of exhausted particles and swirled dust particles to the measured particulates and coarse particles in Tunnel A are shown in Figure 8.

The figure shows that particulates accounted for about 90% of all particles and the percentage of coarse particles was small. Exhausted particles emitted from vehicles accounted for a very large percentage (about 70%) of the particulates, followed in order by dust of road pavement and dust of tire rubber. On the other hand, about 70% of coarse particles were of unknown origin. Exhausted particles and swirled dust particles accounted for only about 15% each. Although part of the unknown sources may have been exhausted particles, accounting for a small percentage, and the amount of coarse exhausted particles was very small. Therefore, the effects of exhaust regulations would appear more strongly in particulates than in coarse particles. In this prediction, the ratios were assumed as shown in Table 3.

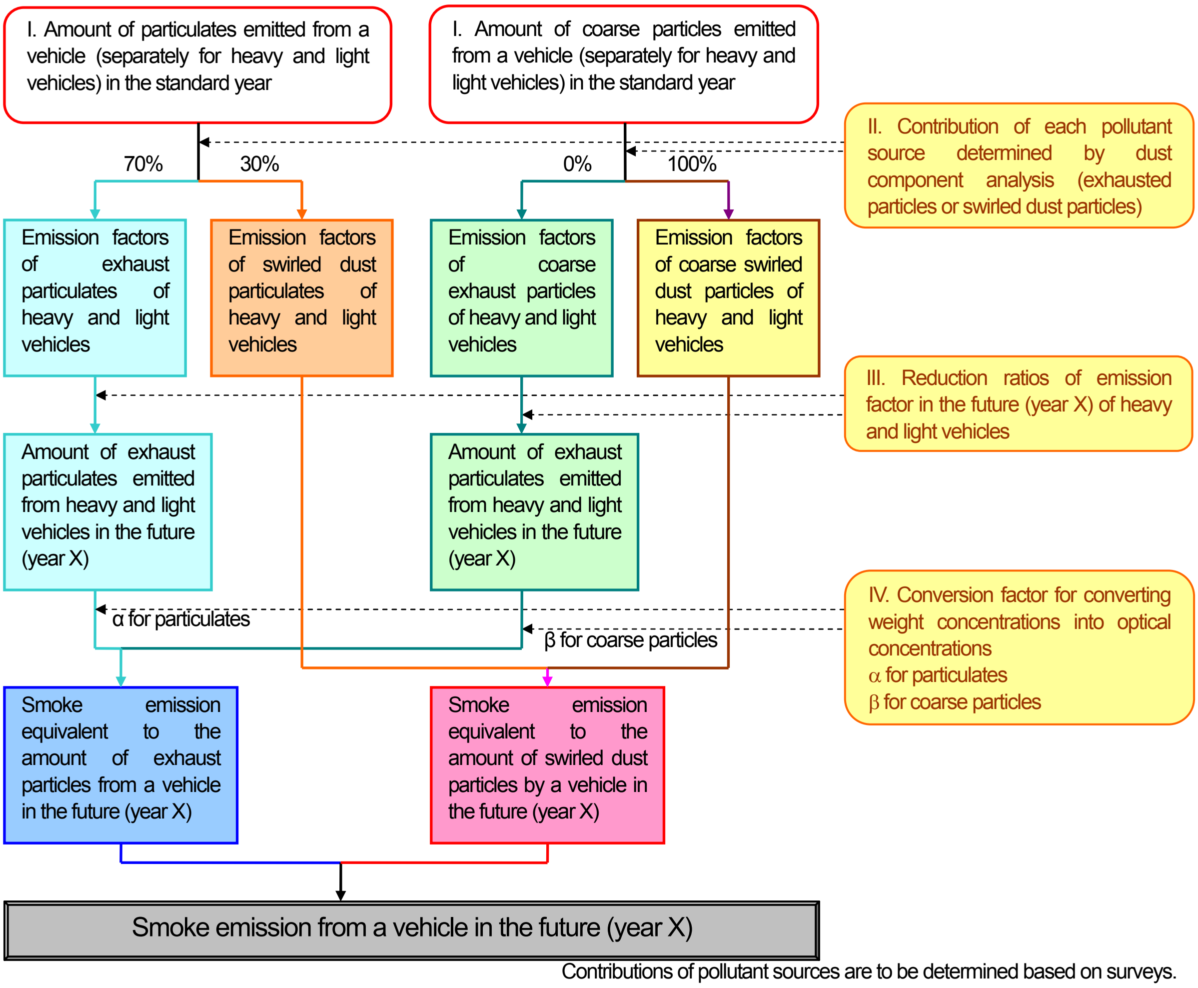

Figure 7. Procedure for estimating future smoke emissions

Table 2. Emissions of particulates and coarse particles from a vehicle (separately for heavy and light vehicles (g/km･vehicle))

	Particulates		Coarse particles	
Results of the survey in 2007 (Tunnel A)	Light vehicle	Heavy vehicle	Light vehicle	Heavy vehicle
	0.060	0.290	-	0.054

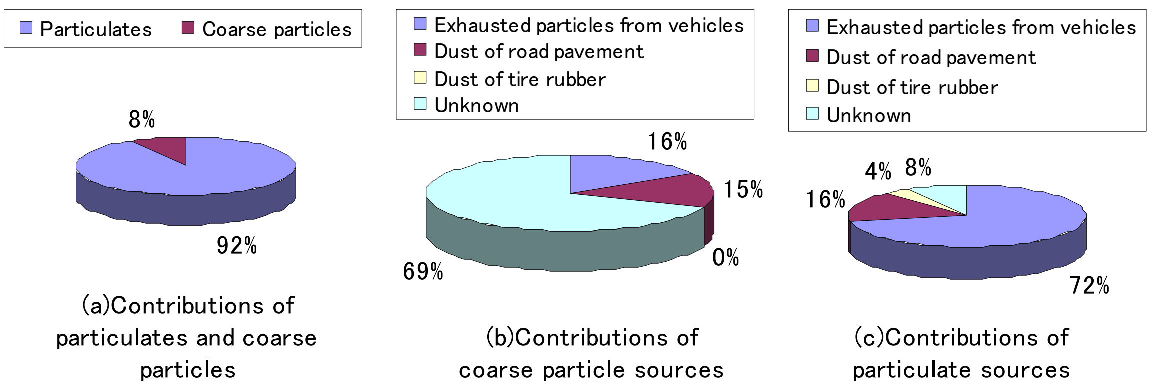

Figure 8. Contributions of particle sources in Tunnel A

Table 3. Contributions of particle sources on particulates and coarse particles (%)

Particulates		Coarse particles	
Exhausted particles from vehicles	Swirled dust particles	Exhausted particles from vehicles	Swirled dust particles
70	30	0	100

(3) III. Reduction ratios of emission factors of heavy and light vehicles in the future

The future emissions to be used for designing ventilation systems should be designed based on the exhaust regulations, vehicle model and type in the standard year. Changes in vehicle type from the present to the future should also be considered.

The reduction ratios of heavy and light vehicles in the future were estimated as follows.

Step 1: Vehicles were classified into 8 typical models, and annual emissions [3)] were determined based on the results of bench tests.

Step 2: The emissions were weight-averaged with the percentages of vehicle models shown in Table 4, and the emissions from light and heavy vehicles in each year were determined.

Step 3: To consider the recent number of vehicles and the actual number of running vehicles in each year, future emissions were determined for each model year of vehicle by calculating the weighted average with the percentage of each model year shown in Figure 9.

Step 4: The ratio to the emissions from the vehicle model in the standard year was calculated as the reduction ratio.

The calculated reduction ratios from the emissions in 2007 are shown in Figure 10. The figure shows that the emissions will decrease until 2012 for both heavy and light vehicles and thereafter will reach a constant value, which is approximately half of that in 2007.

The percentage of vehicles that meet the exhaust regulations in each year, which was determined using the vehicle model composition shown in Figure 9, was estimated to change as shown in Figure 11.

Table 4. Assumed percentages of vehicle models

Vehicle type				Percentage (%)	Mean semi loaded weight (ton)
Light vehicle	Passenger car (74.6%)	Gasoline-fueled		83.5	-
		Diesel-fueled		16.5	-
	Truck (25.4%)	Gasoline-fueled	Light	26.1	1.25
			Intermediate	11.6	1.60
			Heavy	3.3	2.15
		Diesel-fueled	Light	9.9	1.30
			Intermediate	16.1	1.70
			Heavy	33.0	2.48
Heavy vehicle		Gasoline-fueled	Light	0.6	3.00
		Diesel-fueled	Intermediate	0.4	2.02
			Heavy	99.0	11.53

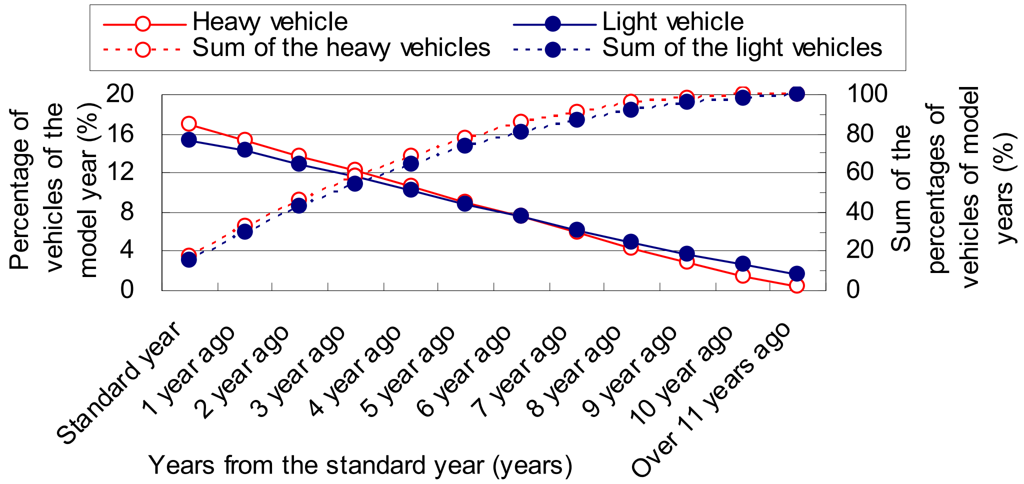

Figure 9. Vehicle model composition in each year

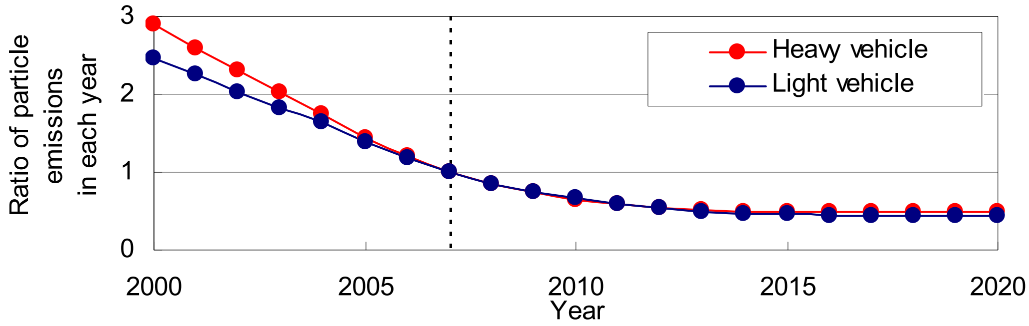

Figure 10. Predicted reduction ratio of particle emissions

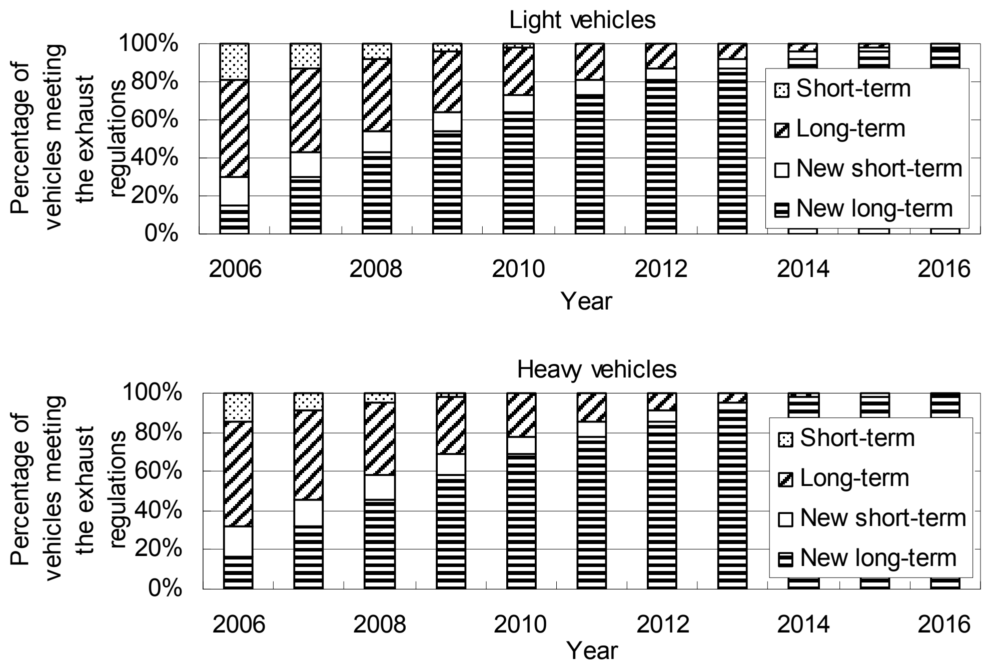

Figure 11. Changes in the percentage of vehicles meeting the exhaust regulations

(4) IV. Conversion factor for converting weight concentrations into optical concentrations

To estimate future smoke emissions by considering exhaust regulations, conversion factors are needed to convert the amount of particulates and coarse particles into optical concentrations, which will then be used for designing ventilation, because the amounts of exhaust particles from vehicles, which are expressed in weight concentration, are predicted to decrease. The conversion factors were determined using the following equation:

$$K=\alpha\cdot Mf+\beta\cdot Mc \qquad \text{... (3)}$$

where, K : the optical concentration (m^{-1}) by visibility sensor(VI), Mf : the weight concentration (g/m^3) of particulates, Mc : the weight concentration (g/m^3) of coarse particles, α : the conversion coefficient (m^2/g) for particulates, β : the conversion coefficient (m^2/g) for coarse particles.

Equation (3) was transformed into Equation (4). A single correlation analysis was conducted on a plot of the relationship shown in Figure 12, in which Mf/Mc is plotted on the X axis and K/Mc on the Y axis. The inclination of the resultant regression line is α, and the intercept is β.

$$\frac{K}{Mc}=\alpha\frac{Mf}{Mc}+\beta \qquad \text{... (4)}$$

The conversion factors for converting weight concentrations into optical concentrations used were the means of the values calculated from measurements in 2000 to 2007 shown in Table 4.

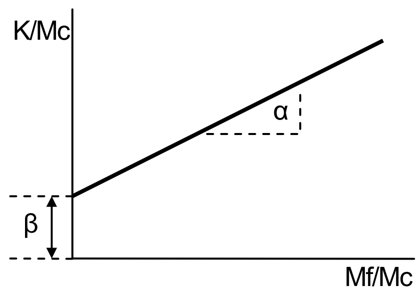

Figure 12. Method for determining conversion factors α and β (simulated equation)

Table 5. Conversion factors α and β for converting weight concentrations into optical concentrations

Tunnel	Year	α of particulates	β of coarse particles
A	2007	5.49	3.10
C	2002	10.17	0.19
D	2003	4.37	3.02
E	2004	8.51	2.13
	Mean	7.1	2.1

3.5 Estimated future smoke emissions

Smoke emissions were predicted for each year using the methods described above. The predicted smoke emissions are shown in Figure 13. The smoke emissions were estimated to decrease until about 2013: up to about 0.3 m^2/km/vehicle for light vehicles and about 1.5 m^2/km/vehicle for heavy vehicles.

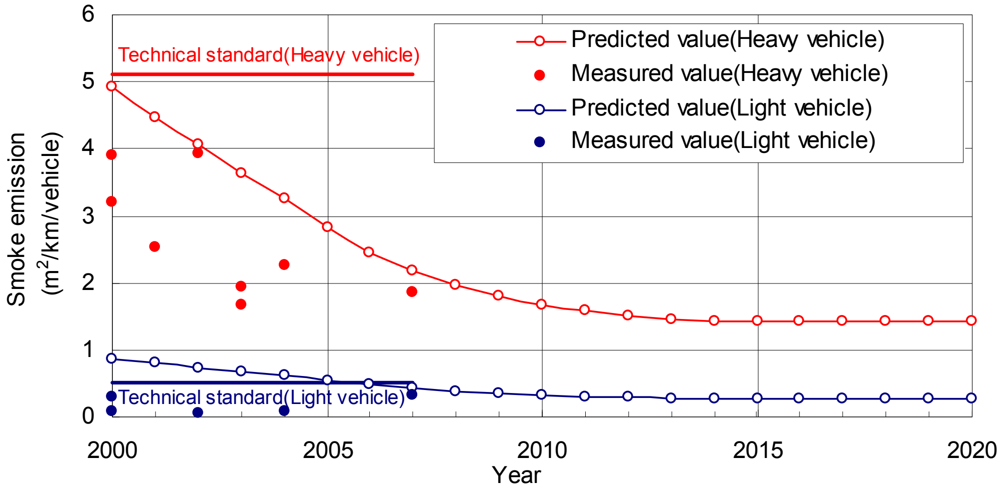

Figure 13. Estimated smoke emissions in the future

3.6 CO emissions

Today, ventilation systems are designed by assuming the CO emission value of 7 liter/km/vehicle. All CO values measured during the measuring are shown in Figure 14. The CO emission value must be set on the safe side to ensure its acute toxicity does not affect human health even when it fluctuates. Therefore, ventilation systems must be designed for a CO emission value that covers almost all measurements, which was found to be about 5 liter/km/vehicle (coverage ratio: 95%) for both light and heavy vehicles.

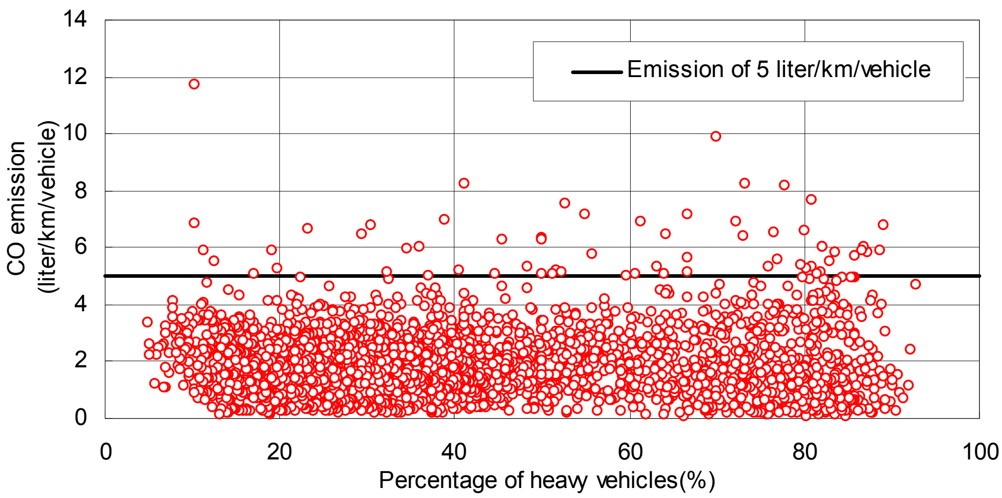

Figure 14. CO emissions (2000 to 2007)

4. Revision of emission values for designing ventilation systems

Technical standards for the ventilation systems of road tunnels in Japan are summarized in the “Technical Standard for Road Tunnel”, and the standards are explained in the “Technical Standard for Road Tunnel (for Ventilation) and Practical Guide”. Based on the results of this study, the standard smoke emissions from each vehicle in the latter were revised for the period when the emissions will decrease (2008 to 2012) and after 2013 when the emissions will be constant. The new standards [4] are shown in Figure 15.

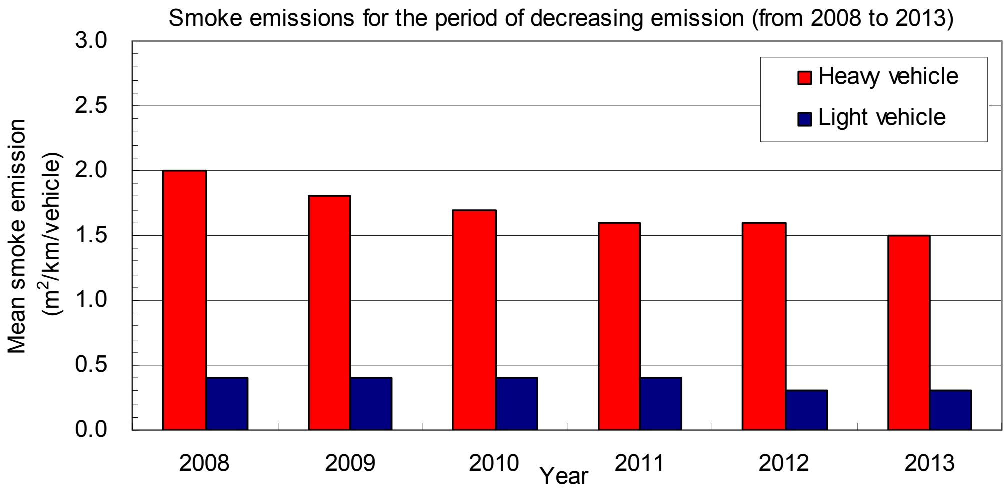

Figure 15. New standards ("Technical Standard for Road Tunnel (for Ventilation) and Practical Guide")

5. Conclusions

This study monitored the exhaust gas concentration in road tunnels in service over several years and investigated changes in the amounts of harmful substances emitted from vehicles and the emissions of pollutants to be ventilated from a vehicle, which are to be used for designing ventilation systems of road tunnels. The following results were obtained:

1) The concentrations monitored in 2007 in a road tunnel in service reconfirmed that the emissions per vehicle have decreased every year.

2) The smoke emission values to be used for designing ventilation systems were estimated to decrease in the future until 2013 for both heavy and light vehicles: to about 0.3 m^2/km/vehicle for light vehicles and 1.5 m^2/km/vehicle for heavy vehicles.

3) The CO emission value to be used for designing ventilation systems, which must be set on the safe side to ensure its acute toxicity does not affect human health even when it fluctuates, was decided to be about 5 liter/km/vehicle, which can cover almost all measurements.

Thereafter, the emissions will be checked and revised by monitoring future changes in exhaust regulations.

References

1) Japan Road Association: Technical Standard for Road Tunnel (for Ventilation) and Practical Guide (in Japanese), October, 2001.

2) Public Works Research Institute of the Ministry of Construction: Study report on trip generation rate and correction factor for smoke emissions per vehicle to be used for designing tunnel ventilation (in Japanese), Joint study report of PWRI No. 114, March 1995.

3) National Institute for Land and Infrastructure Management: Basis of calculations of vehicle emission factors (in Japanese), Technical Memorandum of NILIM No. 141, December 2003.

4) Japan Road Association: Technical Standard for Road Tunnel (for Ventilation) and Practical Guide (in Japanese), revised in 2008.